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## **Breathability Characterization of Ballistic Fabrics, Including Shear Thickening Fluid- Treated Fabrics**

**by Wai K. Chin and Eric D. Wetzel**

**ARL-TR-4392**

**March 2008**

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Weapons and Materials Research Directorate, ARL**

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## 1. Introduction

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### 1.1 Motivation

Body armor reduces the risk of injury or death in U.S. Army Soldiers by providing protection against threats such as fragmentation and shrapnel. However, in addition to providing ballistic protection, the body armor must be designed to be comfortable. Protective apparel that is pleasant and convenient to wear is much more likely to be worn and therefore improves its efficacy in protecting the soldier.

For a garment to be comfortable, such factors as weight, thickness, flexibility, fit, and thermal management should be considered. One aspect of thermal management is breathability. Heat is dissipated by the body through perspiration and subsequent evaporation. Clothing that has low breathability will reduce the ability of sweat to evaporate, which can lead to higher heat retention and increased discomfort.

The objective of this study is to systematically evaluate the breathability of a series of fabrics commonly used in ballistic armors. Materials that are more breathable are likely to provide more comfort than materials that are less breathable.

Most of the experiments in this report utilize a single layer of fabric. However, realistic armors are typically composed of many fabric layers, typically within the range of 15–50 layers. To guide our understanding of layering effects, some breathability experiments are performed on multilayer fabric samples.

### 1.2 Shear Thickening Fluid (STF)-Treated Fabrics

Our set of fabrics include a range of fiber types, architectures, and coatings. Included in this study are fabrics treated with STFs. STFs are materials that are flowable at low stress levels but transition to a solid-like state when subjected to higher stresses (1–2). Previous experiments have shown that adding STFs to high performance fabrics such as nylon and Kevlar\* can increase the protective properties of these fabrics, especially against puncturing threats (3–6).

The STFs used in this and previous studies consist of submicron particles suspended in a carrier fluid. Micrographs of STF-treated fabrics (figure 1) show that the STF fills spaces between yarns and filaments in a woven fabric. Therefore, the STF addition could block some of the transport paths through woven fabrics, which could lead to a decrease in breathability. An important aspect of this study is to quantify the effect of STF treatment on breathability. For this reason, the breathability of Kevlar and nylon fabrics after various STF treatments is measured.

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\* Kevlar is a registered trademark of the E.I. DuPont de Nemours and Company.

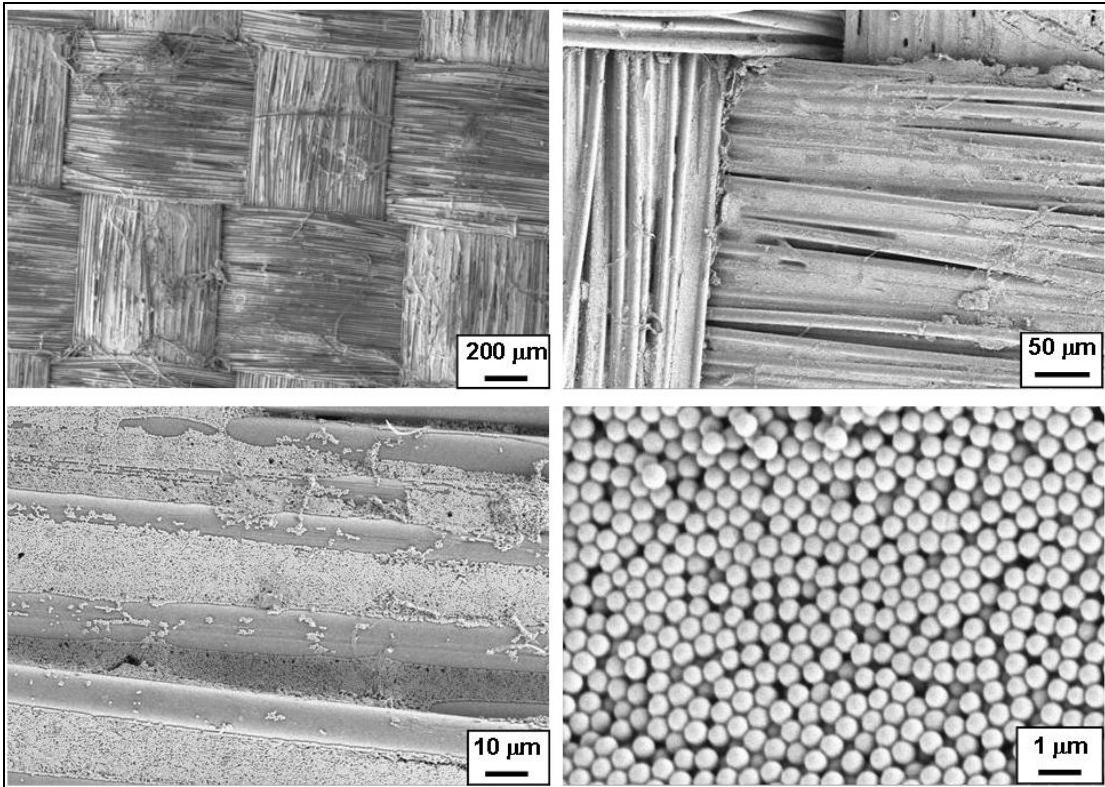


Figure 1. Micrographs of STF-treated style 706 Kevlar fabric.

## 2. Experimental

### 2.1 Materials

Table 1 summarizes the materials tested, and figure 2 shows photographs of the untreated fabrics. A standard camouflage, cotton-nylon blend battle dress uniform (BDU) fabric is measured to represent baseline garment breathability. Style 706 Kevlar represents a typical body armor ballistic fabric. Style 779 Kevlar (also known as Correctional Kevlar) is a more tightly woven protective fabric, with lower denier yarns and more yarns per inch (ypi) than the S706 fabric. The nylon fabric has different fiber properties but a similar architecture to the S706 fabric. The Argus<sup>\*</sup> material is a thermoplastic-coated, woven Twaron<sup>†</sup> fabric that is used for multithreat ballistic and stab vests. SpectraShield<sup>‡</sup> is a cross-ply laminate of unidirectional Spectra fibers in a polyethylene copolymer matrix.

<sup>\*</sup> Argus is a registered trademark of Argus Technologies.

<sup>†</sup>Twaron is a registered trademark of Enka B.V.

<sup>‡</sup>SpectraShield is a registered trademark of Honeywell Performance Fibers.

Table 1. Summary of materials tested.

Sample ID	Source	Description
BDU	<sup>a</sup>	CMM07: Camouflage polyester/cotton blend
S706 Kevlar	<sup>b</sup>	Style 706: 34 × 34 ypi, 600d KM2 Kevlar, plain woven
S779 Kevlar	<sup>b</sup>	Style 779: 70 × 70 ypi, 200d K159 Kevlar, plain woven
Nylon	<sup>c</sup>	31 × 32 ypi, 840d heat set nylon, plain woven
Argus	<sup>d</sup>	27 × 27 ypi, 840d Twaron 2000, thermoplastic-coated
SpectraShield	<sup>e</sup>	SpectraShield LCRw: 1300d Spectra 1000, cross-ply laminated
STF-Kevlar	ARL	706 Kevlar fabric treated with 15%–20% PEG-based STF
STF-nylon	ARL	Nylon fabric treated with 15–20 weight-percent PEG-based STF
UDS STF-Kevlar	ARL	706 Kevlar fabric treated with 15%–20% UDS-based STF
MSTF-Kevlar	ARL	706 Kevlar fabric treated with <1% PEG-based STF

<sup>a</sup>Barre Army Navy (Barre, VT).

<sup>b</sup>Hexcel Reinforcements (Anderson, SC).

<sup>c</sup>Performance Textiles (Greensboro, NC).

<sup>d</sup>Barday (Charlotte, NC).

<sup>e</sup>Honeywell (Colonial Heights, VA).

Note: ARL = U.S. Army Research Laboratory.



Note: All photos to same scale, as indicated in lower right image.

Figure 2. Photographs of untreated fabrics.

The S706 Kevlar fabric (uncoated) has a hydrophobic finish (Hexcel CS-898). The S779 Kevlar has a scoured finish (Hexcel CS-800). The nylon fabric was used in its greige state.

All STF treatments in this study were applied to the fabrics at ARL. Specific STF properties and processing routes are discussed elsewhere (3–6). The STF consists of 450-nm diameter, spherical silica particles at 52% v/v in the carrier fluid. In most cases, the STF liquid phase is 200 Mw polyethylene glycol (PEG). In one case, a proprietary silicone fluid, called “UDS,” is used instead of PEG to create the STF. The UDS silicone fluid is highly hydrophobic, allowing for the fabrication of an STF-treated fabric that is water repellent. Note that PEG is water soluble, so that PEG-based STF treatments are not inherently water resistant. Comparing PEG- and UDS-based STFs allows us to quantify if hydrophobicity in the STF coating impedes breathability.

Three of the STF-treated samples have weight loadings of 15%–20% STF. These weight loadings have been shown to produce effective penetration and puncture resistance (3–6). In order to determine the effect of STF loading on breathability, two additional weight loadings were characterized. One sample, called “LSTF-Kevlar,” has a weight loading of ~7% STF, while a second sample, called “MSTF-Kevlar,” has a weight loading of <1% STF.

Note that scoured (Hexcel finish CS-800) S706 Kevlar fabric was used for STF-treated materials, since the STF coating does not apply well to fabrics with a water-repellent finish. The same greige nylon fabric was used for untreated and STF-treated experiments.

All samples were run as single-layer experiments. In addition, experiments were run on two- and five-layer S779 Kevlar samples.

## 2.2 Procedure

Breathability measurements were performed based on E96/E96M-05, Standard Test Methods for Water Vapor Transmission of Materials (7). Approximately 30 g of distilled water was placed in a 50-mL (50.8-mm-diameter × 25.4-mm-high) diffusion cup at room temperature (figure 3a). The mass of the water was carefully weighed and recorded. A 67-mm-diameter circle of fabric was then placed on top of the diffusion cup with a 50-mm-diameter circular exposed surface and sealed using a threaded lid (figure 3b). The mating faces of the lid and container have interlocking grooves to seal the fabric edges, so no secondary sealant material, such as wax, was required. The cup, water, and fabric were weighed and then placed in an oven maintained at 37 °C and 10% relative humidity. Temperature and humidity control were maintained through a continuous dry nitrogen purge and drying agent inside the chamber. Temperature and humidity were monitored using a VWR\* digital temperature/hygrometer.

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\*VWR is a registered trademark of VWR International, Inc.

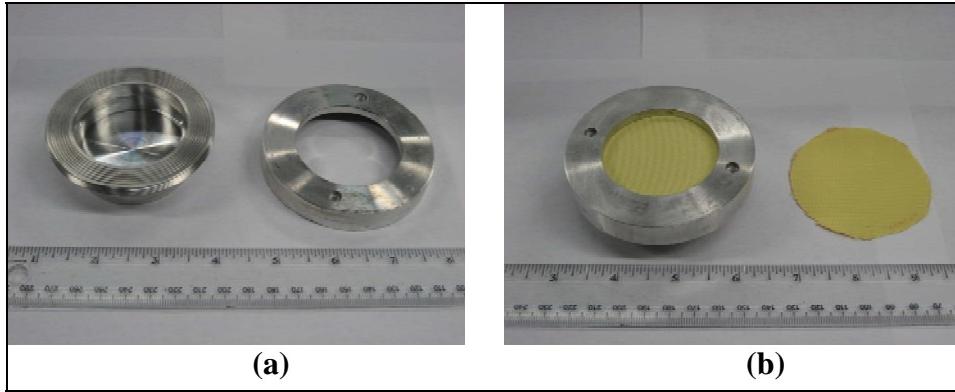


Figure 3. Sample cup with water (a) and with fabric clamped and sealed (b).

Weight loss measurements were performed by removing the diffusion cup from the oven and weighing and recording total system mass. Measurements were first taken at 4-hr intervals on the first day, and then 3× per day for a total of 4 days or until sufficient data was obtained to determine the constant weight loss rate of the samples. Three runs were performed for each material, with new material samples used for each experiment.

### 3. Results and Discussion

Figure 4 shows mass loss as a function of time for the untreated fabrics. The plotted data is the average of three samples run simultaneously, with standard deviation for each point also shown. Table 2 shows the time-averaged water vapor transport (with units of grams/hour × square meter) for these fabrics. To calculate these values, a linear interpolation of each sample's mass loss data (up to 72 hr) was performed. The slopes of these lines (mass loss rate in grams/hour) were then averaged over the three samples for each fabric type and normalized by the exposed fabric area ( $19.6 \text{ cm}^2$ ) to generate an average water vapor transport value. Figure 5 compares the average water vapor transport for the different fabrics in graphical form.

The data show that the BDU fabric has the highest breathability, with the S779 fabric exhibiting similar breathability values. The other uncoated woven fabrics, S706 and nylon, both show ~20% less breathability than the BDU and S779 fabrics. The higher breathability of the S779 as compared to the S706 fabric could be due to its lower thickness, 0.18 vs. 0.23 mm, respectively (manufacturer data). The thermoplastic-coated fabrics, Argus and SpectraShield, show very low breathability, with values less than 5% that of the BDU fabric. This result is not surprising since the continuous polymer films are expected to block most moisture transport.

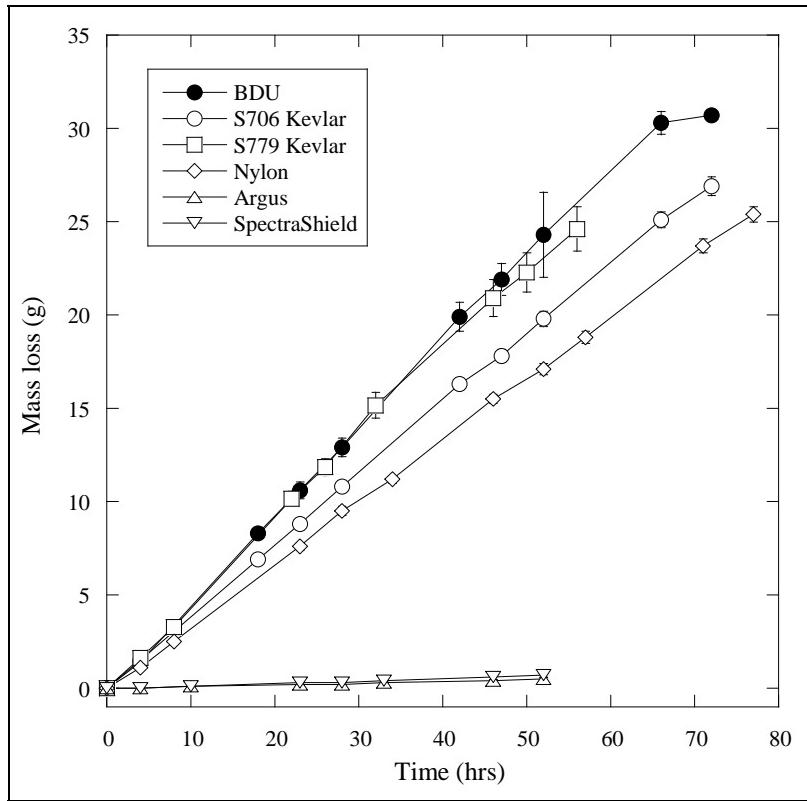


Figure 4. Average water mass loss as a function of time for untreated fabrics. (Error bars indicate standard deviation of each averaged value.)

Table 2. Average and standard deviation of water vapor transport for different fabrics.

Sample ID	Water Vapor Transport (g/hr • m <sup>2</sup> )	Standard Deviation (g/hr • m <sup>2</sup> )
BDU	228	8.66
S706 Kevlar	192	3.57
S779 Kevlar	224	11.20
Nylon	170	2.55
Argus	4.58	0.102
SpectraShield LCR	7.13	0.509
STF-Kevlar	162	11.2
STF-nylon	174	3.06
UDS STF-Kevlar	144	5.09
MSTF-Kevlar	171	1.02
LSTF-Kevlar	163	9.17

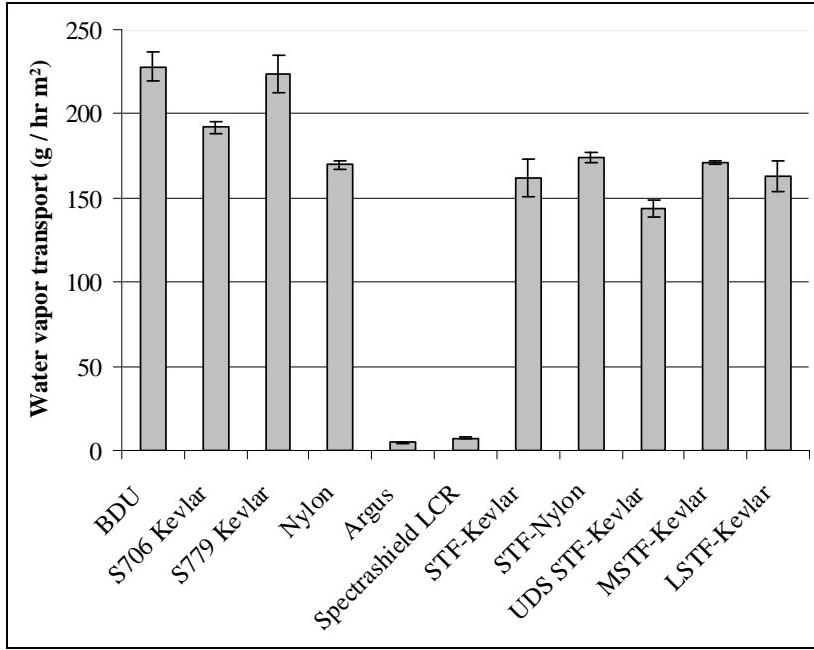


Figure 5. Average water vapor transport for different fabrics. (Error bars show standard deviation.)

Figure 6 shows average mass loss as a function of time for the STF-treated fabrics. The average values of water vapor transport are tabulated in table 2 and plotted in figure 5. Adding the STF treatment to the S706 Kevlar fabrics appears to slightly decrease the water vapor transport by ~15%. The UDS-based STF treatment gives a slightly lower mass loss than the PEG-based STF treatment, with a breathability ~25% lower than the untreated Kevlar fabric. The MSTF-Kevlar and LSTF-Kevlar breathabilities are 11% and 15% less than the untreated S706 Kevlar fabric. Note that the breathability of the LSTF and STF-treated fabrics are nearly identical. The STF-treated nylon fabric shows a breathability that is nearly identical to the untreated nylon fabric.

Figure 7 shows water mass loss as a function of time for one-, two-, and five-layer S779 Kevlar samples. The average water vapor transport values are tabulated in table 3 and plotted in figure 8. The results show little difference between one- and two-layer specimens. The water vapor transport is measurably reduced for the five-layer sample but its breathability is still many times greater than the thermoplastic-coated materials, such as Argus and SpectraShield. For example, the trend in water vapor transport with respect to layer count does not appear to be sufficiently well behaved to justify extrapolation when estimating the breathability of a 30-layer S779 armor.

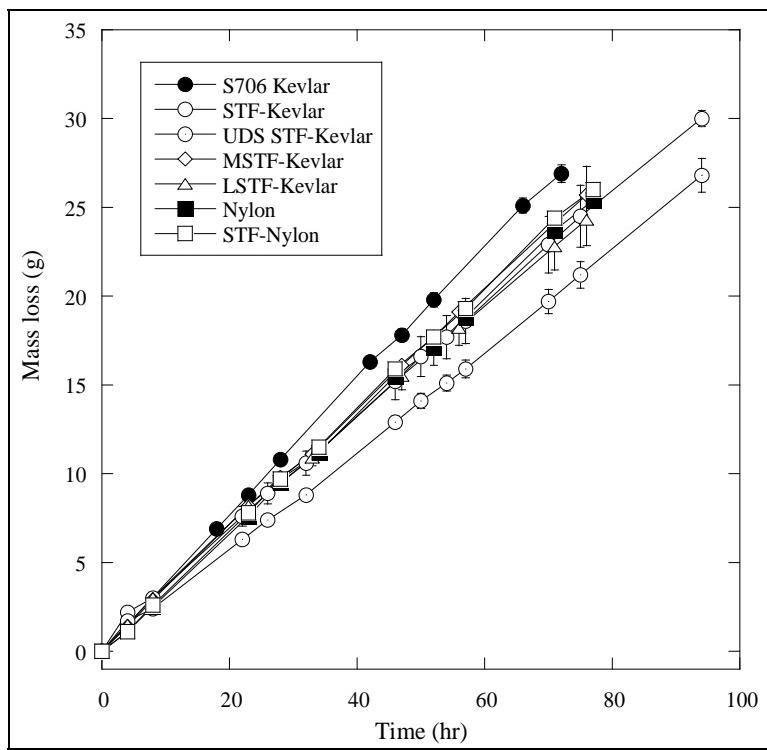


Figure 6. Water mass loss as a function of time for STF-treated fabrics.  
(Error bars indicate standard deviation of each measurement.)

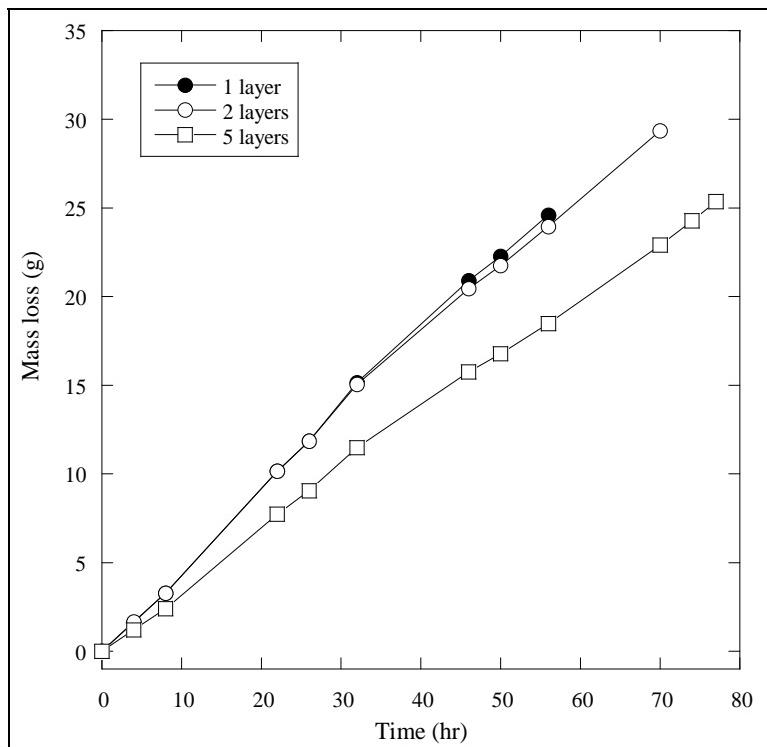


Figure 7. Water mass loss as a function of time and layer count for S779 Kevlar fabric.

Table 3. Effect of layer count on water vapor transport for S779 Kevlar fabric.

Layer Count	Water Vapor Transport (g/hr • m <sup>2</sup> )	Standard Deviation (g/hr • m <sup>2</sup> )
1	224	11.2
2	217	5.6
5	168	8.7

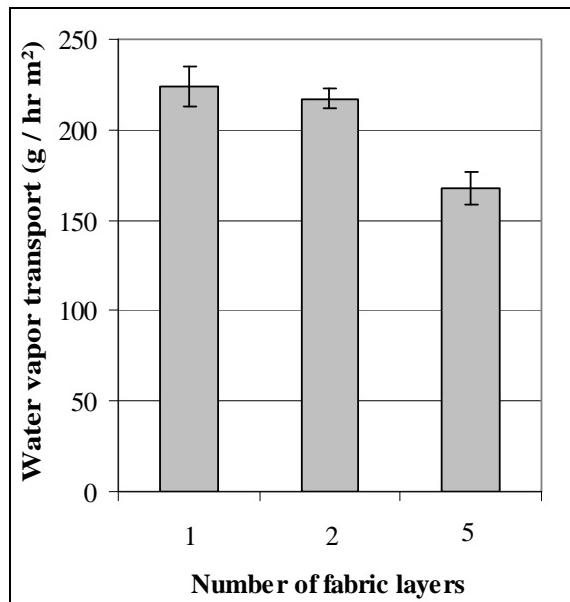


Figure 8. Average water vapor transport for one-, two-, and five-layer S779 Kevlar samples.  
(Error bars show standard deviation.)

#### 4. Conclusions

The results show that, in general, uncoated ballistic fabrics offer good breathability that is only slightly lower than conventional military clothing. In contrast, plastic-coated fabrics such as Argus and SpectraShield have very low breathability. These materials could cause discernable discomfort if worn in warm climates, unless special carrier design is implemented to manage moisture and heat.

The STF treatments appear to slightly decrease fabric breathability, although, in general, the fabrics are still highly breathable. Compared with STF treatments that are based on water-soluble materials, the use of hydrophobic STF treatments appears to have only a marginally detrimental effect on breathability. These results indicate that armors composed of STF-fabrics should have only slightly lower breathability than comparable conventional armors so that the design of comfortable STF-based armors should be realizable.

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